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by
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EXPLOSIVE CONVECTIVE ADJUSTMENT IN A HYDROSTATIC OCEAN MODEL

ABSTRACT

The hydrostatic fourth-order-accurate semi-collocated (modified Arakawa "a" grid) DieCAST Ocean Model simulates explosive convective adjustment, including less-than-complete watermass mixing and counter - diffusive processes not addressable by popular diffusive convective adjustment approaches. This is shown by model application to explosively unstable 3-d flow over a slope. Even with such explosively unstable initial state, the hydrostatic DieCAST model gives robust and rapid stabilization through unstable plume dynamics. The degree of watermass mixing during convective adjustment is sensitive to the model Prandtl number, which may be chosen to mimic the effective turbulent Prandtl number of convective adjustment in the ocean.

1.1 Introduction

Diffusive convective adjustment schemes, including instant convective adjustment which is equivalent to infinite vertical diffusivity, do not address *counter-diffusive* heat transport processes that may occur in convective adjustment and deep water formation. In order to be able to address such processes, the DieCAST Ocean Model and its lineage do not relate vertical diffusivity to the need to maintain convective stability. Instead they directly model the convection (Dietrich and Roache, 1991)), albeit using a hydrostatic approximation.

Such counter-diffusive vertical heat transport would be unlikely if the northern ocean heat source were at its bottom, rather than from the poleward heat transport of the ocean general circulation. However, the ocean bottom is nearly insulated and the poleward heat transport is large compared to any bottom heat source. This may lead to counter - diffusive vertical heat transport during wintertime deep penetrative convection, as may occur near the tropopause in the atmosphere in response to bottom heating.

Rather spectacular counter-diffusive behavior occurs in laboratory experiments having sudden density increase at the top of a fluid between two vertically oriented plates (see Appendix 1), in stark contrast to classic simple Bernard convection, where such counter-diffusive vertical heat transport does not occur. These experiments may be relevent to the dynamics of deep water formation.

Wintertime cooling events can lead to a turbulent surface mixed layer from which sparsely distributed cold plumes or "chimneys" jet downward. The plumes draw water from the cold mixed layer, with only partial dilution of the cold surface water by mixing processes before the cooled mixture plunges downward in quasi-adiabatic plumes. Such *incomplete mixing* poses a challenge to non-convecting ocean general circulation models. (Herein, "non-convecting" refers to models that do not admit the vigorous small-scale plumes needed to directly simulate acceptably rapid convective adjustment. Instead, they sometimes use large horizontal dissipation parameters, together with diffusive convective adjustment, which may be needed to avoid numerical instability or otherwise unphysical behavior of small-scale modes.)

This study is motivated by the need for convecting ocean model that can address incomplete mixing and counter-diffusive heat transport; and our desire to relate the potential benefits of an alternate approach - *direct simulation* of convective adjustment - used by DieCAST and its lineage dating back to the original SOMS model (Dietrich et. al, 1987).

Such direct simulation is quite appealing and worth seriously exploring now that extremely powerful computers exist which allow more effective use of the direct approach. This study is a start.

Previously, using a non-hydrostatic model, Lin and Dietrich (1994), herein below "LD94", show that the final mixture density in downward plumes or "chimneys" depends on the effective turbulent Prandtl number. Indeed, as discussed by LD94, the Prandtl number parameter can be used in a physically meaningful way to control the degree of mixing and entrainment into numerically modeled convective plumes. The LD94 numerical experiments, which were motivated by the aforementioned laboratory experiments (see Appendix 1), *clearly demonstrate the counter-diffusive nature of the finite-amplitude chimney-like plumes in the experiments.*

In the real ocean, the important penetrating plume potential density is determined mainly during small-scale near-surface eddy mixing. The mixture potential density is determined by rapid mixing as near-surface material gathers into plumes and then plunges quasi-adiabatically (due to the large scales compared to those involved in the mixing processes of the surface mixed layer) downward until reaching a matching potential density level. Although the full convection details involve some interesting and significant salinity and compressibility effects when the convective plumes penetrate deeply into the ocean (Garwood, et. al, 1994), the important near-surface potential density mixing may be addressed phenomenologically while using a linear Boussinesq equation- of-state relating density to temperature only, as done in the LD94 study.

Thus, the critical mixing is highly localized near the ocean surface rather than occurring throughout the deeply convecting real ocean, as assumed by diffusive convective adjustment approaches. Instead, the deep plume dynamics includes counter-diffusive vertical transports that are difficult to address by non-convecting models, and they cannot be fully represented by popular ad hoc diffusive convective adjustment approaches.

The deep plume dynamics involves advection of cold dense water formed near the surface downward through relatively low density intermediate levels to deeper levels where the potential density matches that of the cooled surface water. Thus, the deep plumes advect anomalously cold water down through levels where the water is relatively warm (less dense) to colder levels below. This means that the "eddy heat transport" is *toward warmer water.* This is a basic *counter-diffusive* transport process in real oceans. The cold plumes are dynamically coupled to the rising of warm water nearby, which occurs on a generally larger scale to replace the cold plume material as it leaves the turbulent surface layer.

Representation of such natural convective adjustment processes as diffusive "subgrid-scale" processes would require *negative* vertical diffusivity in intermediate level regions where counter-diffusive heat transport by subgrid scale plumes occurs, which, of course, would lead to disastrous explosive numerical instabilities rather than proper representation of nature. Yet subgrid scale convection representation as a diffusive process has been popular in large-scale ocean modeling: large *positive* vertical diffusivities are used to "parameterize" subgrid scale convective processes that are fundamentally not diffusive. Although this ad hoc approach may lead to erroneously deep and diffuse thermoclines, it is popular, apparently because there is no simple alternative when using models whose small-scale modes become numerically unstable when using the small diffusivities needed for rapid convective adjustment.

Deep convection counter-diffusive processes were addressed by LD94 using a non-hydrostatic model of convective adjustment. Herein, through application of the DieCAST Ocean Model to explosive convective adjustment in the strongly unstably stratified problem described in Section 1.2, *we show that the essence of natural convective adjustment counter-diffusive processes may also be described by hydrostatic ocean models.* Though, such a problem would rarely occur in nature (see Appendix 2), it provides for a stiff test to our approach. The DieCAST Ocean Model and its lineage (beginning with the SOMS model: Dietrich, et al., 1987) have this capability, because of their low numerical dispersion and robustness when using the low lateral eddy viscosity and heat diffusivity required to model small-scale rapid convective adjustment that occurs in nature.

1.2 The Problem

A new fourth-order-accurate version of the DieCAST Ocean Model having greatly reduced numerical dispersion (Dietrich, 1997) is applied to dense plume flow down a slope in the idealized problem of Beckmann and Doscher (1997) (hereafter BD97).

The BD97 problem is as follows. The modeled region is rectangular with longitude-independent depth. The northern "sill" end is 500 m deep. The southern end is 3600 m deep. A sill slope of 0.01 is prescribed (which is also the cell aspect ratio). The domain is a 320 km square. The horizontal and vertical resolutions are uniform, 5 km and 50 m respectively (72 layers). Only the southern two latitudes are at the maximum 3600 m depth, with linear variation from the northern sill.

The initial temperature is 20 deg C. Salinity is not included. A linear equation of state with a 0.0002/deg C thermal expansion coefficient is used. The entire domain is closed and insulated. Free slip lateral conditions

and standard nonlinear bottom drag conditions are applied (quadratic drag coefficient = 0.005).

At the beginning of each time step, the bottom layer temperature is set to 17.5 deg C in the northernmost three zones, between 0.75 and 0.875 normalized longitudinal coordinate (0 at western boundary, 1 at eastern boundary). No wind forcing is included.

The horizontal viscosity and thermal diffusivity are 1000 m^2/sec during the first 50 days. They are reduced to 100 and 10 m^2/sec, respectively, during days 50-100.

The vertical viscosity and thermal diffusivity are 10 cm^2/sec during the first 50 days. Vertical diffusivity is reduced to 1 cm^2/sec during days 50-100.

1.3 Model Results

The BD97 problem described in Section 1.2 may not correspond well to nature and may not allow a clear demonstration of the advantage of numerical models having accurate, low dissipation numerics (see Appendix 2). However, the artificially large diffusion specified for the first 50 days provides a strongly convectively unstable day 50 result from which to demonstrate explosive convective adjustment by the hydrostatic DieCAST ocean model. No ad hoc convective adjustment scheme is used by DieCAST. The model is thus allowed to overturn unstable regions through its basic dynamics.

Figure 1 shows day 50 bottom velocity and density distribution. The unphysically large dissipation parameters (see section 1.2) are such that the cell Reynolds (or Peclet) number is O(1), which gives results similar to the upwind differencing used by BD97. The lack of significant eddies to mix the plume is due to these large dissipation parameters.

Figure 2 shows day 50 vertical north-south section of density through the artificially cooled top-of-the-sill bottom water. The large horizontal diffusion has lead to a convectively unstable region above the sloping bottom, while not allowing proper convective adjustment of the region. Conventional ad hoc diffusive vertical mixing and instant convective adjustment approaches (the zero Prandtl number limit described by LD94) would lead to rapid homogenization of the unstable region, while in nature plumes would form (finite effective turbulent Prandtl number) that overturn the water thus forming a thin cold layer along the bottom of the originally unstable region. Again, we note that the details of this BD97 problem are not realistic, since the convectively unstable intermediate depth tongue would rarely occur in nature (see Appendix 2). However, the BD97 problem can be used to illustrate the rapid convective adjustment of the DieCAST model that takes place under these conditions, as it does under natural *surface* cooling conditions.

Figures 3 and 4 show the rapid convective adjustment after reducing the viscosity and thermal diffusivity at day 50 to allow convection to develop. The adjusted state has a *thin* cold layer along the bottom, contrary to the *fat* diffused mixed region that would result from conventional ad hoc diffusive or instant convective adjustment approaches. This has major implications to thermohaline circulation. For example, the geostrophic thermal wind (that is, the distribution of the horizontal density gradient) is entirely different from the conventional result.

These results show that the hydrostatic DieCAST Ocean Model can simulate rapid convective adjustment without excessive dilution of the convective plumes, thus avoiding the major problem of conventional ad hoc approaches (see Section 1). This capability is needed to fully represent thermocline dynamics associated with intermediate and deep water formation in nature.

Although realistic sill modeling may not inherently involve strong convection as simulated here, it may be desirable to directly model small scale modes that develop along nearly vertical fronts in regions where the stratification is very small (or even slightly negative) and the Rossby radius of deformation is small (or unreal both physically and mathematically). Thus, it may be very desirable that sill models have realistically small dissipation and low numerical dispersion.

1.4 Disclaimers

Although the hydrostatic approximation may not be accurate for some aspects of convective plume dynamics, it may give more realistic "explosive" convective adjustment than possible using popular ad-hoc diffusive schemes in the problem of Section 1.2, as seen in the results described in Section 1.3, because the degree of mixing may be controlled by the model turbulent Prandtl number, as shown by LD94; and counter-diffusive processes may be addressed that are inherently contrary to diffusive approaches. As a follow up to our direct response to BD97 (Dietrich, et. al, 1998) we have demonstrated herein the advantage of our approach through the simple BD97 test problem.

The hydrostatic convection is somewhat faster than may occur with fully non-hydrostatic models because of the neglect of vertical inertia effects, but this may be compensated when the fastest growing convective modes are not actually resolved (the usual case for ocean models). A primary requirement for large-scale ocean models is that convective adjustment occur in a time scale that is small compared to processes that disrupt the convective stability and dominate large-scale ocean dynamics.

The hydrostatic representation of convective instability has good basis from simple energy considerations, but does not exactly conserve potential plus kinetic energy; the potential energy change goes entirely into horizontal kinetic energy, while vertical velocity "goes along for a ride" and is bounded (thus not leading to unlimited unphysical instability) through its determination by the incompressibility constraint. More accurate convection can be simulated by minor modification of DieCAST involving a numerical perturbation expansion (through iteration within a time step) on the nonhydrostatic (vertical acceleration) terms (Dietrich, et al., 1987). However, this may not be needed for the purpose of getting more realistic convective adjustment than conventional ad hoc approaches. The main error may be the effect on inertial overshoots and associated internal wave generation when the plume water reaches its deep equilibrium level. This issue is not addressed here.

1.5 Summary

We have shown that hydrostatic ocean models, particularly DieCAST, can effectively simulate rapid convective adjustment processes that are not addressable by conventional ad hoc diffusive or instant convective adjustment approaches. These processes, particularly up-gradient heat transfer, may be critical to climate modeling through their effects on thermocline dynamics and associated thermohaline circulation.

1.6 Concluding Remarks

Although model comparison through well-designed test problems is widely recognized as an important part of computational fluid dynamics research, choosing test problems that either have discontinuous forcing (as in the present case — see Appendix 2) or whose solutions have major input from subgrid scale effects is not advisable. These problems are not easily subjected to the rigors of resolution sensitivity studies that are widely recognized as an extremely important part of model validation and comparison (see discussions along these lines by Roache, et al., 1986, Roache, 1989).

The present convective adjustment study shows a possible alternate approach to the unphysical but popular ad hoc parameterizations of subgrid scale convection dynamics. Because of the subgrid scale effects, validation of this alternate approach may be possible only by application to real problems such as coastal polynia (Gawarkiewicz and Chapman, 1995; Jiang and Garwood, 1995), and comparison with the limited observations available in high latitude ocean regions, but we have herein shown the potential for positive results that are difficult to obtain using popular ad hoc approaches.

Appendix 1: Deep Convective Adjustment Experiments

In the laboratory experiments, seen in an Imperial College mechanical engineering tour at the ICLASS (1985) meeting [1], a stably stratified two-layer fluid between two closely spaced vertically oriented plates is suddenly unstably stratified by turning the plates 180 degrees around a central axis. The resulting initially unstable interface between the two layers quickly develops Rayleigh-Taylor instability with a characteristic wavelength determined by a viscous cutoff. As the resulting unstable plumes grow, they mix the fluid across the interface. The vertical profile of the horizontally averaged density thus quickly develops a uniform region around the original interface depth location where it was initially discontinuous, reflecting side-by-side plumes of the contrasting density. As the expanding central region becomes neutrally stratified, the top and bottom of this "mixed" region remain unstably stratified. Mushroom-like structures develop as an early nonlinear effect reflecting the fact that the most unstable wavelength has increased in order to communicate across the mixed layer, with largest growth rates near the two unstably stratified regions at the top and bottom of the quasi - neutral mixed layer. Thus, the natural scale of the "plumes" grows as the mixed layer thickens. Later, the fluid "flips" on a large scale, roughly matching the total depth, as do observed "chimneys" in the ocean, *leading to dense bottom water formation. The entire process appears strikingly similar to deep water formation in the ocean.*

Interestingly, the keynote speaker at ICLASS was Dr. D.B. Spalding, co-originator of some of the main ideas used by the diffusive Mellor-Yamada turbulence closure scheme widely used by ocean modelers (Launder and Spalding, 1974), yet, somewhat ironically, its inherently diffusive nature does not allow it to address even the basic dynamics of this experiment during its finite-amplitude penetrating plume stage.

Appendix 2: Shortcomings of the BD97 Test Problem

The BD97 test problem described in Section 1.2 is not an ideal test of high order, low dissipation ocean models, because:

A) Its forcing is resolved by only *one* vertical cell.

Accurate and realistic simulations are unlikely. The closed northern boundary combined with fixed cold bottom temperature at the top of the sill forces extremely large vertical and horizontal *deep* water cross-isotherm advection in the absence of unphysically large diffusion. Comparably strong

[1] Attended by Dr. David Dietrich with his Father, Dr. Verne Dietrich, a leading expert in spray technology

cross-isotherm advection does not occur in nature except possibly in suddenly and strongly cooled surface mixed layers. In nature, the cold bottom water comes mostly from horizontal (along-bottom) transport *through open boundaries* into any particular region, rather than adiabatically near the bottom as occurs in the BD97 problem.

B) Its forcing artificially maintains a temperature discontinuity, even if applied over more than one vertical cell.

Forcing a discontinuity virtually eliminates the advantage of higher order accuracy in the DieCAST Ocean Model. Indeed, because of this discontinuity and poorly resolved forcing the chosen problem is ill designed to show the advantages of a model that uses high order accuracy, realistically low dissipation and low dispersion numerics, such as the DieCAST Ocean Model. This problem is further discussed by Dietrich, et al., 1998.

Because of the resulting artificially large cross-isotherm advection, especially in the vertical (where huge vertical downwelling into the artificially maintained cold region occurs), larger vertical diffusivities are needed to avoid overshoots than would be needed by good models in realistic problems.

In general, it seems that today in ocean modeling the focus may be too much on parameterization of subgrid scale effects, when they are actually quite secondary in *real* problems that *can* be addressed (including El Nino dynamics and the general circulation of large ocean basins such as the Gulf of Mexico), and thus should be the focus of model comparisons.

Ocean modeling efforts have already drawn serious criticism including that by the meteorological modeling community. There is considerable expertise outside our tight little (but growing) community. Ignoring such expertise may risk criticism by even larger communities, as our work comes to light during these times of growing public interest in ocean related issues such as El Nino, global warming, and fisheries losses.

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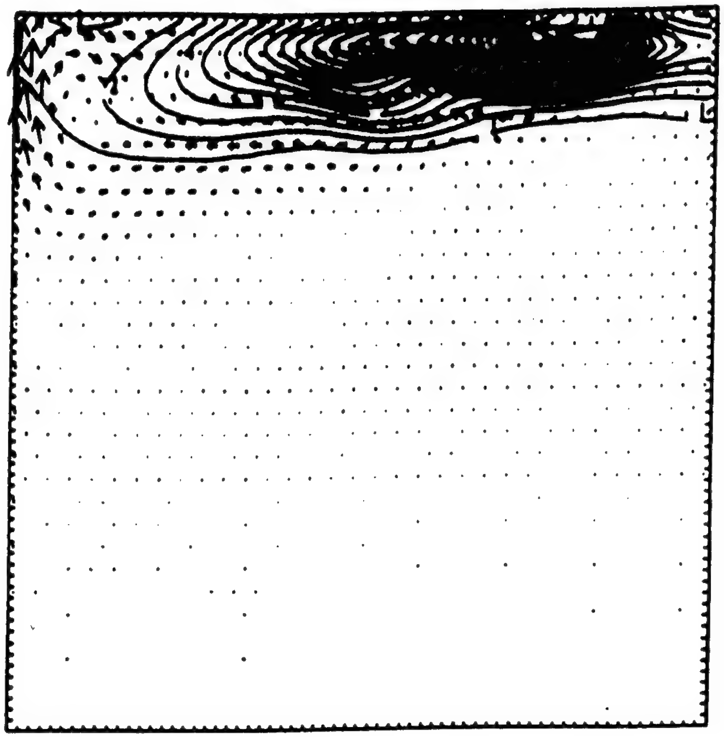


Figure 1: Day 50 bottom layer density anomaly and velocity after unphysically large diffusion during model days 0-50. The maximum velocity = 17.8 cm/sec.

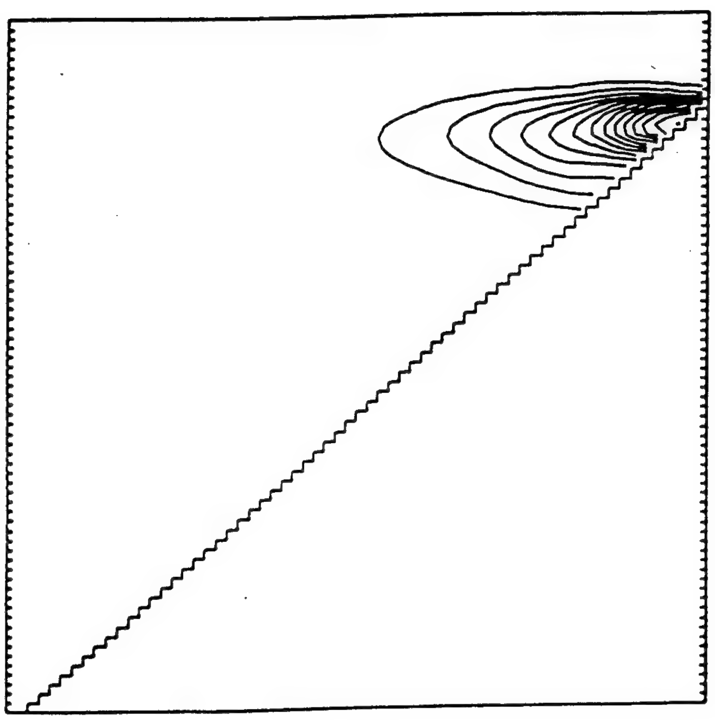
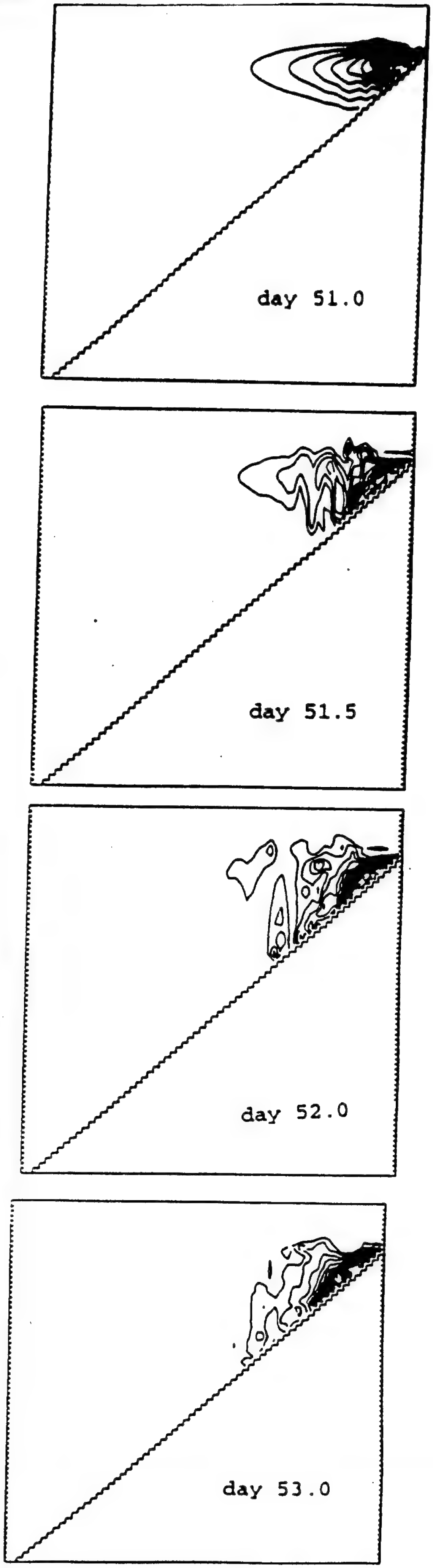


Figure 2: Day 50 vertical cross-section of density anomaly 200 km from western boundary (120 km from eastern boundary).



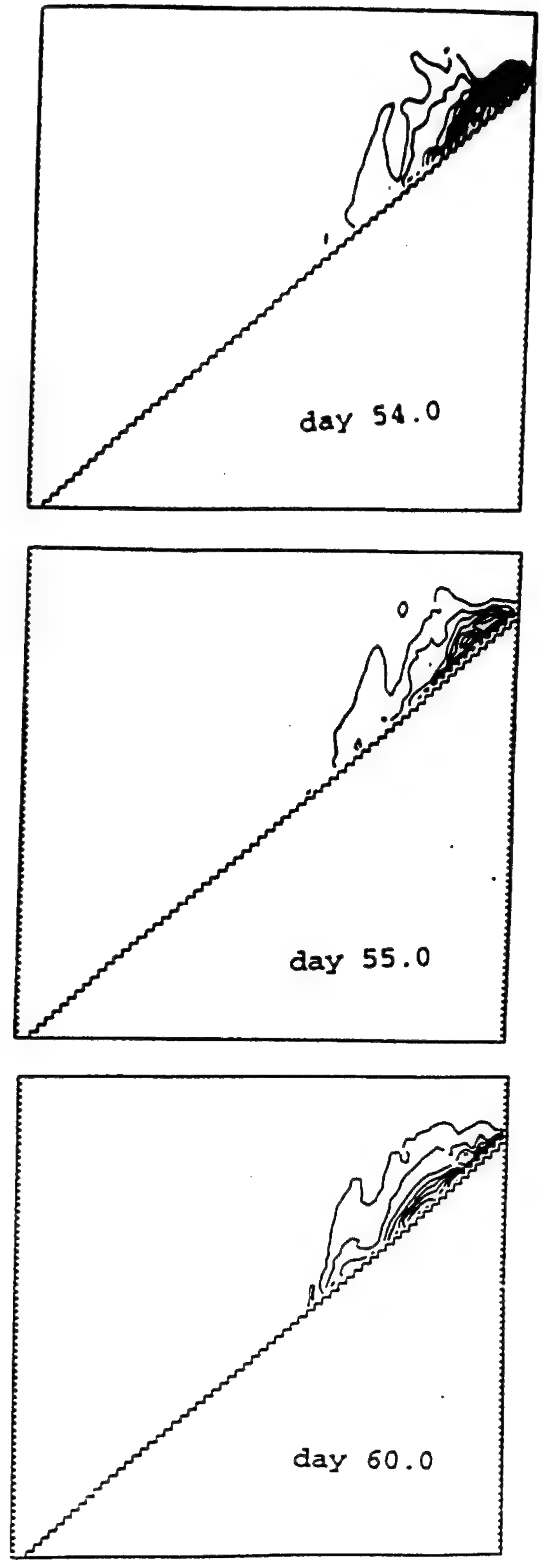
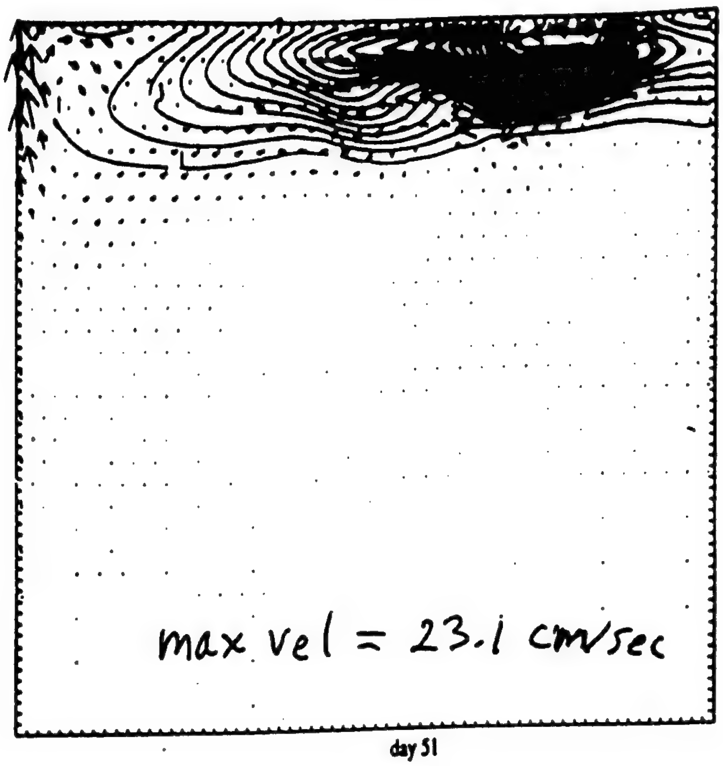


Figure 3: Density anomaly evolution showing time evolution of convective adjustment in same cross-section as in Figure 2. Explosively rapid convective adjustment between days 51 and 52 leads to thin dense plume along the bottom.



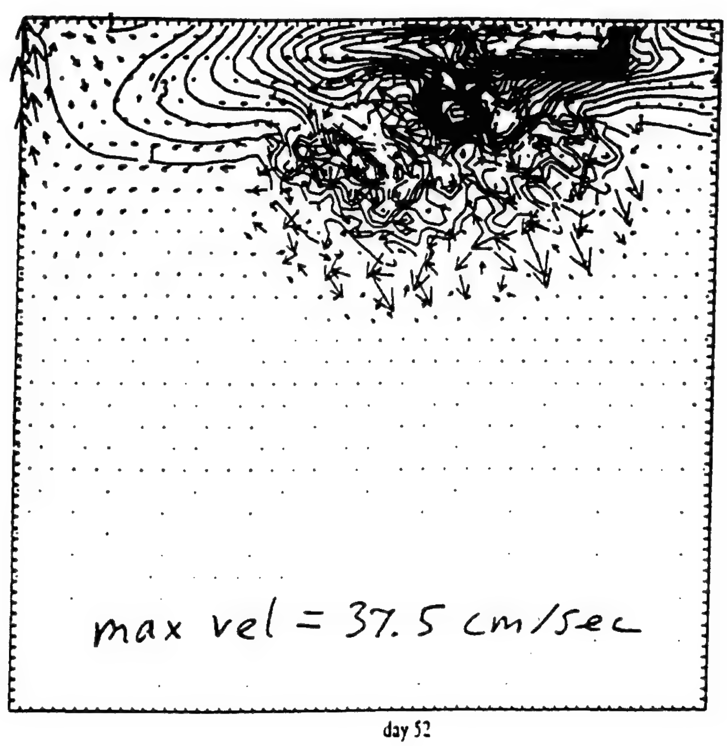


Figure 4: Days 51 and 52 bottom layer density anomaly and velocity.

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Under funding from the Office of Naval Research (ONR), this Mississippi State University Center for Air Sea Technology (CAST) research with the hydrostatic fourth-order-accurate semi-collocated (modified Arakawa "a" grid) DieCAST Ocean Model simulates explosive convective adjustment, including less-than-complete watermass mixing and counter-diffusive processes not addressable by popular diffusive convective adjustment approaches. This is shown by model application to explosively unstable 3-d flow over a slope. Even with such explosively unstable initial state, the hydrostatic DieCAST model gives robust and rapid stabilization through unstable plume dynamics. The degree of watermass mixing during convective adjustment is sensitive to the model Prandtl number, which may be chosen to mimic the effective turbulent Prandtl number of the convective adjustment.

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